

EFFECTS OF ARTIFICIAL RECHARGE AND PHYSICAL BARRIER ON SEAWATER INTRUSION

Roger LUYUN Jr¹, Kazuro MOMII², Kei NAKAGAWA³
and Masahiro TAKAHASHI⁴

¹Student Member of JSCE, Ph.D. Student, United Graduate School of Agricultural Sciences, Kagoshima University
(1-21-24 Korimoto, Kagoshima 890-0065, Japan)

²Member of JSCE, Dr. of Agri. Sci., Professor, Dept. of Environmental Sciences and Technology,
Kagoshima University (1-21-24 Korimoto, Kagoshima 890-0065, Japan)

³Member of JSCE, Dr. of Eng., Associate Professor, Dept. of Environmental Sciences and Technology,
Kagoshima University (1-21-24 Korimoto, Kagoshima 890-0065, Japan)

⁴Research and Development Center, Nippon Koei Co. Ltd. (2304 Inarihara, Tsukuba, Ibaraki 300-1259, Japan)

Laboratory experiments were performed to investigate the effects of the application of surface recharge, injection recharge, and the installation of a cutoff wall in repulsing seawater intrusion. Repulsion of about 5% and 6% were achieved by surface recharge and injection recharge, respectively. Doubling the recharge flux increased the repulsion to about 8% and 12%. Numerical simulations have shown that the optimum location for injection recharge application is near the toe of the saltwater wedge. Injection recharge becomes less effective when applied farther and higher from the toe of the saltwater wedge. As such, injection recharge was found to be a more effective than the surface application in repulsing the saltwater intrusion. Cutoff wall was found to be the most effective as the residual saltwater was completely flushed out by the freshwater discharge. The application of surface recharge after installation of the cutoff wall however, has no effect on the removal time of the residual saltwater.

Key Words: *Artificial recharge, cutoff wall, injection well, surface recharge, saltwater intrusion*

1. INTRODUCTION

In coastal areas, excessive groundwater abstraction has led to seawater intrusion into coastal aquifers. Coupled with the continuous sea level rise due to global warming, seawater will encroach farther inland and threaten the available fresh groundwater supply. As about 70% of the world's population lives in coastal zones, the challenges are for the optimal exploitation of fresh groundwater and the control of seawater intrusion¹⁾. The application of artificial recharge from spreading basins or injection wells and the installation of subsurface physical barriers are among several strategies proposed to prevent or minimize saltwater intrusion in coastal aquifers^{2) 3) 4)}.

Parametric studies have been performed to investigate the effect of uniform recharge on

seawater intrusion⁵⁾. The relationships between the intensity and duration of uniform recharge and interface motion were established. While rainfall was the recharge source, these relationships can be compared with artificial recharges. The effect of a recharge facility on saltwater intrusion has also been studied and modeled in the Eastern Sendai area⁶⁾.

Wells that inject low-quality water into a freshwater aquifer to prevent the intrusion of salt water are considered Class V injection wells in the US⁷⁾. The injected water produces a hydraulic barrier by raising the piezometric head of the fresh water aquifer and prevents the saltwater from moving inland.

Subsurface barriers have found their use in some small islands and archipelagos in Japan. They are planned and constructed to control the groundwater flow by storing it for effective use and ensure a

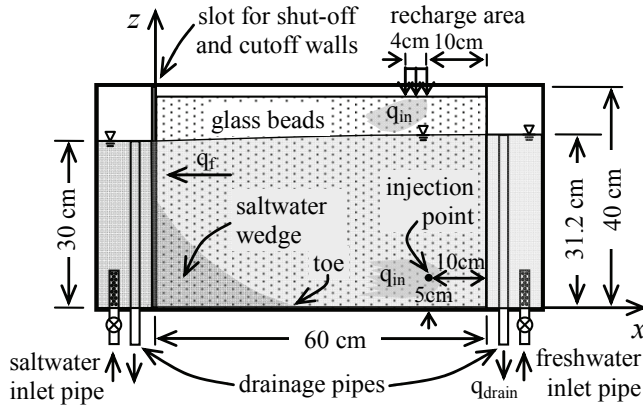


Fig. 1. Schematic diagram of the experimental set-up.

constant extraction of water without causing intrusion of seawater into coastal aquifers⁸⁾. There are about 15 subsurface dams in Japan, seven of which were constructed to prevent saltwater intrusion into coastal aquifers⁹⁾. Experimental and numerical studies have demonstrated that residual saltwater trapped were completely flushed out after installation of cutoff walls¹⁰⁾.

The design and management of recharge facilities and subsurface dams for coastal groundwater systems requires the prediction of the saltwater-freshwater interface movement. The objective of this study is to investigate the effect of the application of recharge, from the surface and by injection, and the installation of a cutoff wall in the control of saltwater intrusion. Laboratory-scale experiments and some numerical analyses are presented. Tidal fluctuation effects were not considered in the study.

2. EXPERIMENTAL SET-UP AND PROCEDURE

The experimental flow tank is 60 cm long, 40 cm high and 4 cm wide as shown in Fig. 1. The tank is bounded on each side by the freshwater (right) and saltwater (left) reservoirs. The main tank was packed with homogenous glass beads with a mean diameter of 1.2 mm modeling a coastal unconfined aquifer. Drainage pipes were used to maintain the salt and freshwater levels at the desired operating height. A slot for the installation of shutoff and cutoff walls separates the main flow tank and the saltwater reservoir. Fine mesh screens prevent the entry of glass beads into the reservoirs and slot. The sides of the cutoff wall are sealed to prevent leakage. Freshwater recharge from the surface was applied through a 4 x 4 cm² source located 10 cm from the freshwater reservoir. Freshwater recharge by injection was applied through a 5 mm diameter tube spanning the entire width of the flow tank perpendicular to the walls. It is located 10 cm from

Table 1. Experimental parameters

Experiment and Case Number	q_f (cm ² /s)	q_{in} (cm ² /s)	q_{in}/q_f (%)
Expt 1. Injection Recharge (Injection Well)	Case 1 0.589	0.114	19.4
	Case 2 0.620	0.250	40.3
Expt 2. Surface Recharge (Recharge pond)	Case 1 0.598	0.120	20.1
	Case 2 0.568	0.238	41.9
Expt 3. Cutoff wall (Physical Barrier)	Case 1 0.583	—	—
	Case 2 0.561	0.120	21.4

the reservoir and 5 cm from the bottom. Small holes are strategically located around the tube to ensure even flow on all angles and the tube is wrapped in wire mesh so that no glass beads will block the flow. The saltwater was dyed with a red food color and its density was kept constant at 1025 g/l. The freshwater recharge was colored blue to act as a tracer and distinguish it from the actual freshwater discharge.

The tanks were initially filled with tap water. The drainage pipes were then adjusted to maintain constant heads of 31.2 cm and 30.0 cm for the freshwater and saltwater reservoir, respectively. This hydraulic gradient allowed for flow of freshwater from the right side to the left side. After the freshwater flow had stabilized, the hydraulic conductivity of the porous medium was determined. The shutoff wall was then inserted and tap water on the left tank was replaced with the red saltwater. The saltwater intrusion process was initiated with the removal of this shutoff wall. Density driven flow progressed until equilibrium condition was achieved forming the characteristic saltwater wedge.

Three types of experiments were performed after the equilibrium saltwater wedge position was reached as shown in Table 1. Experiment 1 involves the application of freshwater recharge by injection simulating an injection well. Experiment 2 involves the application of freshwater recharge from the surface to simulate a recharge pond. The initial freshwater flux (q_f) resulting from the freshwater-saltwater gradient was measured for each experiment and the corresponding recharge application (q_{in}) was computed from this value. Both experiments include two cases. Case 1 has q_{in} value in the range of about 20% of the freshwater flux while Case 2 has q_{in} value approximately 40% of the initial freshwater flux. Specific discharge values are listed in Table 1. Experiment 3 involves the installation of a 30 cm cutoff wall to block the saltwater intrusion. For this experiment Case 1 implies only the installation of a cutoff wall while Case 2 is a combination of cutoff wall and 20% surface recharge. For all tests, the toe position of the saltwater intrusion wedge were observed and recorded.

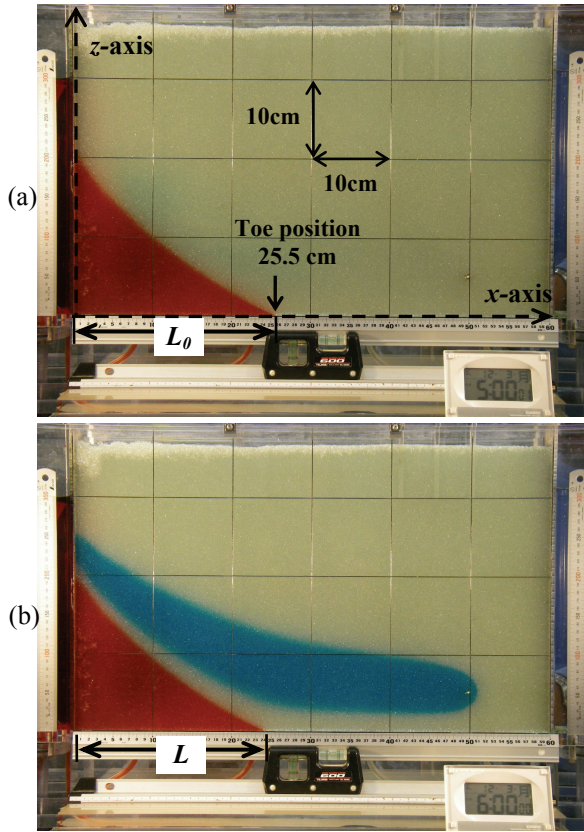


Fig. 2. Recharge by injection (Expt 1 Case 1): (a) initial steady state, (b) after 1 hour.

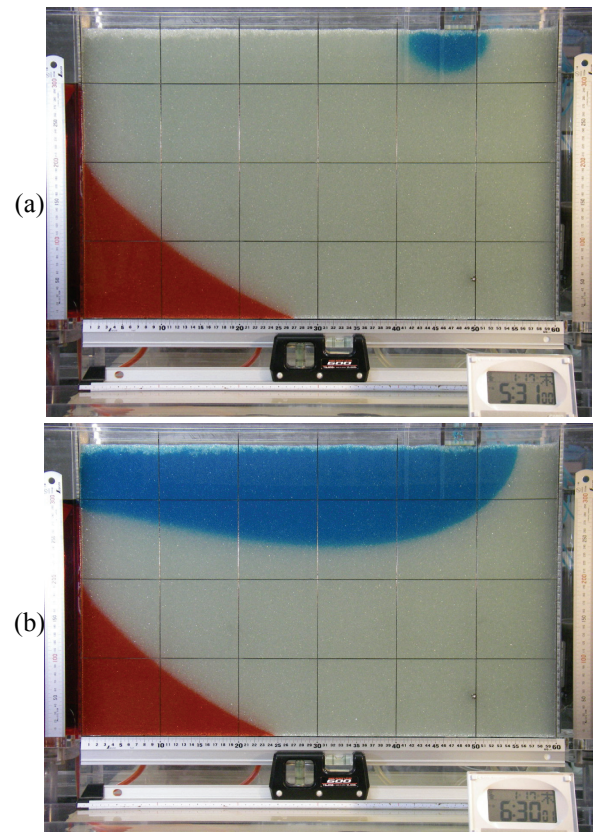


Fig. 3. Recharge from surface (Expt 2 Case 2): (a) 1 min, (b) after 1 hour.

3. RESULTS AND DISCUSSION

(1) Artificial recharge

Sample results for recharge by injection (Expt. 1 Case 1) showing the initial steady state saltwater intrusion and the results after 1 hour of injection recharge are shown in Fig. 2. For the surface recharge, results of Expt. 2 Case 2 after 1 min and after 1 hour of surface recharge are shown in Fig. 3. The red segment is the saltwater wedge while the blue plume represents the recharge flow. The blue freshwater plume acts as a tracer showing the actual recharge flow. As the injection plume flows towards the saltwater wedge and over the transition zone, the reduction in the toe length of the saltwater intrusion can be observed. This reduction was also observed with the surface recharge plume as it traverses the capillary fringe.

The percentage repulsion of seawater was calculated using Eq. 1

$$P(\%) = \frac{L_0 - L}{L_0} \times 100 \quad (1)$$

where L_0 is the initial toe position of the saltwater wedge and L is the final toe position after recharge⁵. The reduction in the saltwater wedge toe position ($L_0 - L$) after recharge application and the corresponding percentage repulsion $P(\%)$ for the

two experiments are shown in Fig. 4. Application of about 20% recharge by injection (Expt. 1 Case 1) achieved a reduction of 1.5 cm from the original toe position or about 6% repulsion of saltwater intrusion. The toe position retreated further to 3.4 cm or about 12% repulsion, when the recharge injection was increased to about 40% (Expt. 1 Case 2). For the surface recharge, the application of about 20% recharge (Expt. 2 Case 1) attained a reduction of 1.2 cm from the original toe position for a little less than 5% repulsion. Increasing the surface recharge to about 40% also improved the reduction to 2.3 cm or about 8% repulsion. These results showed that the application of about 20% recharge could achieve percentage repulsions equivalent to the annual reduction achieved in coastal unconfined aquifers under high annual rainfall condition⁵.

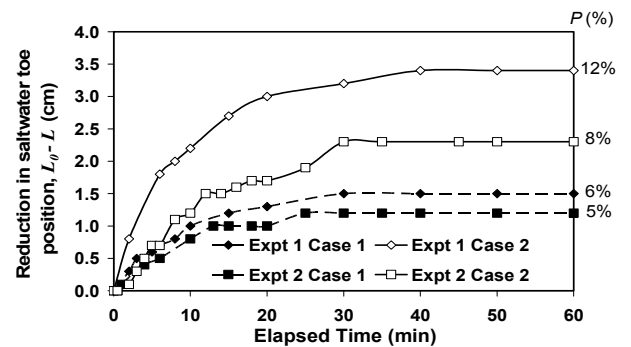


Fig. 4. Reduction in the saltwater wedge toe position with time for Expts. 1 and 2.

Increasing the recharge rate resulted in further increase in the reduction of the saltwater wedge, hence more effective saltwater repulsion. The result also tend to show that recharge by injection was more effective than surface recharge in terms of the reduction of saltwater intrusion.

The freshwater discharge (q_f) transmitted through the system was measured by subtracting the overflow rate at the freshwater reservoir (q_{drain}) from the freshwater input from the overhead tank. With the addition of 20% or 40% recharge, the total freshwater flux through the system should have been increased to $1.2q_f$ or $1.4q_f$, respectively. But because the freshwater level was maintained constant, some of the freshwater input from the overhead tank was drained through the pipes when the recharges were applied. These resulted in lower than expected effective recharge. The effective recharge is the percentage of the applied recharge which is actually transmitted through the aquifer system. The percentage repulsions would have been higher if the applied recharges were fully utilized.

(2) Optimum location of injection recharge

In order to determine the optimum location of injection recharge application, numerical simulation was performed for the recharge by injection (Expt. 1 Case 1). SEAWAT-2000¹¹⁾, which was developed to simulate three-dimensional, variable-density, transient groundwater flow in porous media, was used for the numerical analysis. The simulation employed the finite-difference method. The simulation area is 60 cm by 32 cm in the x and z directions, respectively. The finite-difference grid interval was set at $\Delta x = \Delta z = 0.5$ cm. Zero mass flux boundary condition was fixed at the top and bottom of the simulation area. Constant head boundary conditions were forced at both freshwater and saltwater sides. A longitudinal dispersivity (α_L) of 1.0 mm was set for the porous medium. The transverse dispersivity (α_T) was assumed to be 1/10 that of the longitudinal dispersivity¹²⁾. The porosity (n) and hydraulic conductivity (k) was 0.4 and 1.31 cm/s, respectively. The injected recharge flux (q_{in}) of 0.114 cm²/s was the same as in the experiment but it was given a minimal concentration of 1 mg/l to distinguish it from the freshwater inflow and act as a conservative tracer. The freshwater density was 1000 g/l while the saltwater density was set at 1025 g/l with a salt concentration (C) of 35 g/l.

The model was first validated with the experimental results. The simulation results displaying the saltwater intrusion wedge, velocity vector distribution and concentration profile are shown in Fig. 5. The modeling results in Fig. 5a and 5b may be compared to the experimental results in

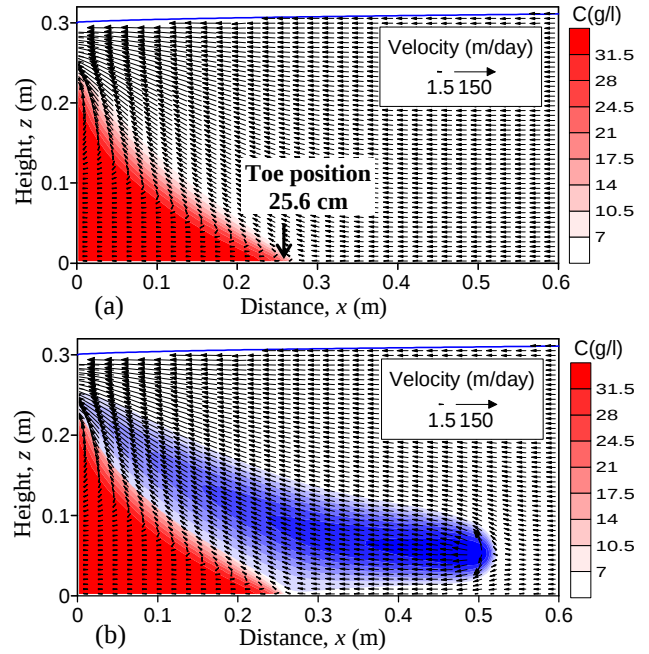


Fig. 5. Numerical simulation of recharge by injection (Expt. 1 Case 1): (a) initial steady state, (b) after 1 hour.

Fig. 2a and 2b. In the simulations, the toe position of the saltwater wedge was measured at the 17.5 g/l concentration line, which is equivalent to a 50% relative concentration (Cr) or the 0.5 isochlor. The relative concentration is defined as Eq. 2

$$Cr(\%) = \frac{\rho - \rho_f}{\rho_s - \rho_f} \times 100 \quad (2)$$

where ρ is the density of the fluid. The initial toe position in the simulation result is 25.6 cm which agrees well with the 25.5 cm for the experiment. The recharge plume in the simulation results are slightly more dispersed than the experimental results. The injection of about 20% recharge achieved a reduction of only 0.8 cm from the original toe position for a little over 3% repulsion of saltwater intrusion. This is lower than the 1.5 cm or 6% repulsion registered in the experiment. This result is reasonable since the use of finite-difference technique may have introduced some numerical dispersions and artificial oscillations on the simulation results. Therefore, future numerical analysis are planned for the same problem using mixed Eulerian-Lagrangian methods, such as the method of characteristics (MOC), or the third-order total-variation-diminishing (TVD) method, to overcome the effects of numerical dispersion and artificial oscillation.

The simulation of injection recharge was repeated at different injection points to determine at which location the maximum repulsion will be achieved. Fig. 6 shows the dotted location of injection points with reference to the saltwater wedge at 0.5 isochlor, and the contour lines

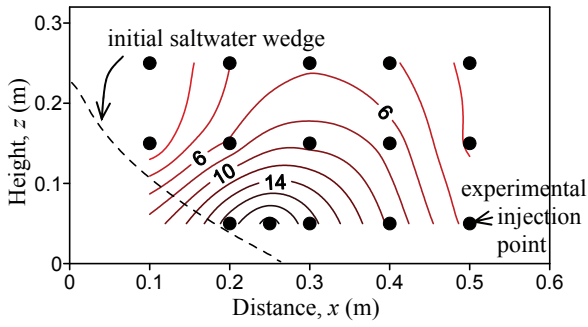


Fig. 6. Percentage repulsion of seawater intrusion based on location of recharge injection points (●).

interpolated from percentage repulsion (%) values computed for each point using Eq. 1. The experimental injection point is at the bottom extreme right and the rest of the points are located above and to the left, separated by 10 cm on both x and y directions. Another point just above the toe position was added to make a more accurate prediction of the effect of recharge near the toe, bringing the total to 15 injection points. Predictably, the maximum repulsion of 21% was achieved at the injection point just above the toe of the saltwater wedge and the two nearest injection points on each side registering repulsion values of about 17%. The repulsion then decreased as recharge is applied higher and farther inland from the toe position. Moreover, as injection recharge was applied above the saltwater wedge and to the left of the toe, the recharge just depresses the wedge but there was little effect in repulsing the toe. In fact no repulsion was measured from the two injection points at the extreme left. These numerical results indicate that the optimum location of injection for maximum repulsion of saltwater intrusion is near the toe of the saltwater wedge. The injection well works by creating a hydraulic barrier that exerts pressure on the salt front repulsing the saltwater intrusion. This is directly effective near the toe of the saltwater wedge and diminishes when recharge is applied farther away from the toe. This also explains why injection recharge is more effective than surface recharge in repulsing saltwater intrusion. Since the surface recharge was applied farther above the toe of the saltwater wedge, its repulsion effects are less than that of the injection recharge.

(3) Subsurface physical barrier

Results for Expt. 3 Case 1 are shown in Fig. 7. Upon installation of the cutoff wall, the residual saltwater trapped in the storage area of the cutoff wall initially advanced (Fig. 7a), peaking at about 45 min (Fig. 7b). Under normal condition (Fig. 5a) saltwater intrudes into the aquifer in a slow density-dependent flow rate and exits along the transition zone maintaining an equilibrium saltwater

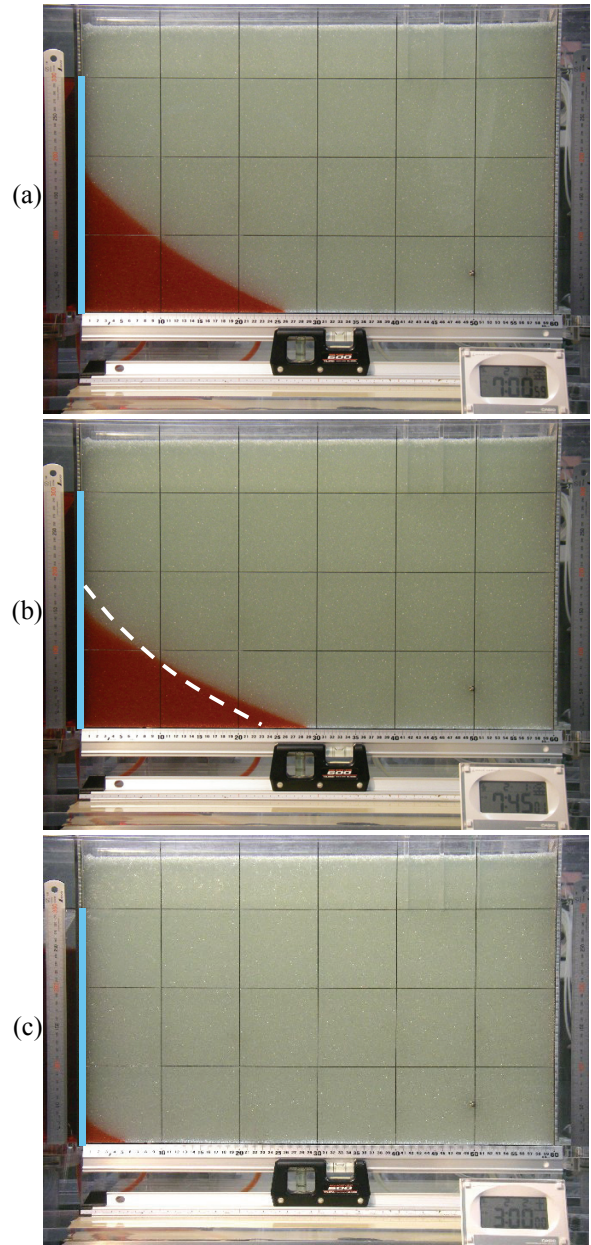


Fig. 7. Cutoff wall experiment (Expt 3 Case 1): (a) after 1 min, (b) peak of advance (45 min), (c) 6 hours before complete removal

wedge. But in this case, because the saltwater supply was blocked, the higher density residual saltwater gradually descends and flatten out making it appear that the toe of the residual saltwater advanced. The dashed line indicates the original saltwater wedge pattern. After this initial advance, the residual saltwater gradually attenuated as dispersed saltwater are flushed out by the freshwater discharge over the cutoff wall (Fig. 7c). Eventually, all the residual saltwater was completely removed from the storage area after 26 hours. The 100% repulsion demonstrated that subsurface physical barriers are very effective in repulsing saltwater intrusion. Numerical simulations of the cutoff wall case based on a different experimental set-up are

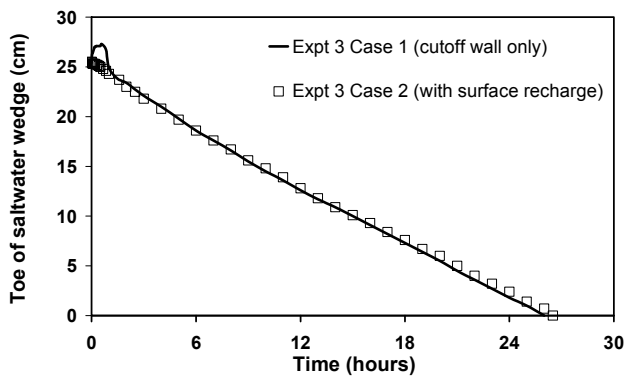


Fig. 8. Transient toe position of the saltwater wedge after cutoff wall installation.

discussed in a previous paper¹⁰.

In order to examine if the removal time of the residual saltwater will be shortened by the application of surface recharge, q_{in} equivalent to about 20% of q_f was applied (Expt. 3 Case 2) after cutoff wall installation. Fig. 8 compares the transient saltwater wedge toe position for each case of Expt. 3. The initial advance of the residual saltwater after cutoff wall installation was not manifested in Case 2. However, both cases exhibited an almost constant attenuation of the saltwater wedge. This indicates that the application of surface recharge has no effect on the removal time of the residual saltwater in the storage area of the cutoff wall, at least based on this experiment.

4. CONCLUSION

Laboratory experiments were performed in a flow tank to determine the effectiveness of the application of artificial recharge, by injection and from the surface, and the installation of a cutoff wall, in repulsing saltwater intrusion. The percentage repulsions achieved by applying about 20% recharge are comparable to the annual reduction achieved under high rainfall condition⁵. Increasing the recharge rate resulted in a more effective saltwater repulsion. Simulation results have shown that injection point should be located near the toe of the salt water wedge to effect the maximum repulsion of saltwater intrusion. Recharge application becomes less effective if it is applied farther and higher from the toe position of the saltwater wedge, explaining why surface recharge is less effective than injection recharge in repulsing seawater intrusion. As the reduction attained from recharge remains steady over a long period after the recharge is stopped, it is possible to reclaim intrusion-affected aquifers to a reasonable extent⁵. With the continuous rise in sea water level, the effect of artificial recharge on the seawater intrusion could become imperative.

In the cutoff wall installation experiment, the

residual saltwater trapped in the storage area initially advanced, gradually attenuated and was completely flushed out by the freshwater discharge. Additional experiments showed however, that the application of surface recharge after installation of the cutoff wall did not affect the removal time of the residual saltwater. The study demonstrated that subsurface physical barriers are truly effective and offer a more permanent solution to saltwater intrusion, replacing the intruding saltwater with freshwater that could be used for domestic and agricultural use.

REFERENCES

- 1) Bear, J., Cheng, A.H.-D., *Seawater intrusion in coastal aquifers – concepts, methods and practices, Theory and applications of transport in porous media*, Bear, J., Cheng, A.H.-D., Sorek, S., Ouazar, D., Herrera, I. eds., Kluwer Academic Publishers, Dordrecht, The Netherlands, 1999.
- 2) Todd, D.K., *Ground Water Hydrology*, John Wiley & Sons, New York, 1959.
- 3) Dam, J.C. van, *Seawater intrusion in coastal aquifers – concepts, methods and practices, Theory and applications of transport in porous media*, Bear, J., Cheng, A.H.-D., Sorek, S., Ouazar, D., Herrera, I. eds., Kluwer Academic Publishers, Dordrecht, The Netherlands, 1999.
- 4) Oude Essink, G.H.P., Improving fresh groundwater supply – problems and solutions, *Ocean and Coastal Management*, Vol. 44, pp. 429-449, 2001.
- 5) Mahesha A., Nagaraja, S.H., Effect of natural recharge on sea water intrusion in coastal aquifers, *Journal of Hydrology*, Vol. 174, pp. 211-220, 1996.
- 6) Miyagi, M., Kazama, S., Sawamoto, M., The seawater intrusion control by groundwater recharge facility, *Annual Journal of Hydraulic Engineering*, JSCE, Vol. 51, pp. 451-492, 2007.
- 7) USEPA, *Report to Congress: Class V Injection Wells*, Office of Groundwater and Drinking Water, Washington D.C., EPA/ 816-R-99-014t, September 1987.
- 8) Shibasaki, T. and Research Group for Water Balance, *Environmental management of groundwater basins*, Tokai University Press, Tokyo, Japan, 1995.
- 9) Japan Green Resources Agency, *Technical reference for effective groundwater development*, Kanagawa, Japan, 2004.
- 10) Luyun, R. Jr., Momii, K., Nakagawa, K., Fujiyama, S., Saltwater dynamics due to cut-off wall installation in coastal unconfined aquifers: experimental and numerical studies, *Calibration and Reliability in Groundwater Modelling: Credibility in Modelling*, IAHS Publ. 320, pp. 214-219, 2008.
- 11) Langevin, C.D., Shoemaker, W.B., Guo, W., *MODFLOW-2000, the US Geological Survey modular ground-water model – Documentation of the SEAWAT-2000 version with the variable-density flow process (VDF) and the integrated MT3DMS transport process (IMT)*, USGS Open-File Report 03-426, USGS Florida, 2003.
- 12) Goswami, R.R., Clement, T.P., Laboratory-scale investigation of saltwater intrusion dynamics, *Water Resources Research*, Vol. 43, W04418, doi:10.1029/2006WR005151, 2007.

(Received September 30, 2008)